The Impact of Semantically Congruent and Incongruent Visual Information on Auditory Object Recognition across development

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Abstract

The ability to use different sensory signals in conjunction confers numerous advantages on perception. Multisensory perception in adults is influenced by factors beyond low-level stimulus properties, such as semantic congruency. Sensitivity to semantic relations has been shown to emerge early in development, however less is known about whether implementation of these associations changes with development, or whether development in the representations themselves might modulate their influence. Here we use a Stroop-like paradigm that requires participants to identify an auditory stimulus whilst ignoring a visual stimulus. Prior research shows that in adults, visual distractors have more impact on processing of auditory objects than vice versa, however this pattern appears to be inverted early in development. We found that children from 8 years of age (and adults) gain a speed advantage from semantically congruent visual information, and are disadvantaged by semantically incongruent visual information. At 6 years of age children gain a speed advantage for semantically congruent visual information, but are not disadvantaged by semantically incongruent visual information (as compared to semantically unrelated visual information). Both children and adults were influenced by associations between auditory and visual stimuli, which they had only been exposed to on twelve occasions during the learning phase of the study. Adults showed a significant speed advantage over children for well-established associations but no such advantage for newly acquired pairings. This suggests the influence of semantic associations on multisensory processing does not change with age, but rather these associations become more robust and in turn more influential.

Key words: Audition; Vision; Multisensory; Congruency; Stroop

Events in our world provide signals to multiple senses. The ability to use these different signals in conjunction confers numerous advantages on perception. First, senses can be complementary in providing unique kinds of information: for example, only vision can reliably tell us whether we are faced with a grey or a red squirrel. Second, senses often provide redundant information about the same property – for example both visual size and auditory amplitude could be cues to an animal's size. Using multiple redundant cues across senses allows adults to detect stimuli more readily (Stein, Wilkinson & Price, 1996; Lovelace, Stein & Wallace, 2003), respond more accurately (e.g., Ernst & Banks, 2002; Alais & Burr, 2004), and more rapidly (Hughes, Reuter-Lorenz, & Fendrich, 1994).

Studies investigating the development of multisensory perception have found mixed results. There is a body of evidence to suggest that some multisensory abilities are present in early infancy (e.g. Schier, Lewkowicz & Shimojo 2003; Neil, Chee-Ruiter, Scheier, Lewkowicz & Shimojo, 2006; Bremner, Slater, Johnson, Mason & Spring, 2012). However, studies investigating the development of cross-modal cue combination suggest that in some tasks, children do not combine information across senses as adults do until 8 years of age or later (e.g., Nardini, Jones, Bedford & Braddick, 2008; Gori, Del Viva, Sandini & Burr, 2008; Nardini, Bedford & Mareschal, 2010; Nardini, Begus, & Mareschal, 2013; Petrini, Remark, Smith & Nardini, 2014; Jaime, Longard & Moore, 2014; Nardini, Bales & Mareschal, 2015). Considering audio-visual stimuli specifically; children appear to integrate cues more frequently and less selectively than adults (Innes-Brown, Barutchu, Shivdasani, Crewther, Grayden & Paolini, 2011; Adams, 2016), they also show a bias towards auditory stimuli (Nava & Pavani, 2013), which develops into an adult-like visual

dominance across middle childhood. Additionally, children show a diminished McGurk interference effect, which also suggests that they may be processing auditory information over visual information (e.g. Massaro et al., 1986). An early bias for auditory stimuli may partially be explained by the differential experience of the auditory and visual systems in the prenatal environment (e.g. Lecanuet & Schaal, 1996). This developmental shift in the way that audio-visual information is weighted suggests that the mechanisms underlying these processes are changing across this period.

Many studies now show that multisensory perception in adults is influenced by factors beyond simple low-level stimulus properties such as spatial and temporal coincidence. For example, adult multimodal perception is also influenced by how attention is allocated within a scene (Talsma, Senkowski & Soto-Faraco, 2010), as well as by variation in the congruency (in terms of both perceptual and semantic features) between the different sensory inputs (e.g. Heron, Whitaker & McGraw, 2004; Slutsky & Recanzone, 2001; Jackson, 1953). There is a growing body of evidence suggesting that adults are sensitive to the semantic congruency between multisensory signals, and that this influences the way in which these signals are processed enabling more accurate and efficient recognition (e.g. Laurienti et al., 2004; Lehman & Murray, 2005; Senkowski et al., 2007; Chen & Spence, 2010). This could be advantageous as it allows observers to use their previous experiences to improve their chances of making correct perceptual judgments. Semantic congruency is a particularly important factor when sensory reliability is reduced. For example, older adults (whose vision and hearing have become degraded over time) benefit

substantially from semantic congruency when processing audio-visual speech (Maguinness et al., 2011).

Moreover, there is also an impressive body of research considering the development of semantic associations across the first years of life. In particular these studies explore how children develop lexical semantic associations. Infants are capable of associating words with objects in their world by the first year of life (e.g. Schafer, 2005). By two years of age infants show enhanced visual target recognition following a related word prime (Styles & Plunkett, 2009), demonstrating that they are already making semantic associations between auditory and visual stimuli. By two years infants are also able to make some semantic associations between the words in their lexicon (Arias-Trejo & Plunkett, 2009), suggesting that they are beginning to build a representation of semantic associations. The development of these semantic associations is an ongoing process as children create more elaborate representations, acquire new content and structure the existing representations accordingly (e.g. Bjorklund, 1985; 1987). It is clear from this work that children are building semantic representations, across multiple sensory domains, from very early in life. Consequently, these higher level associations have the potential to influence perception through top-down processes, across all of childhood.

We know that multisensory processing changes from infancy, through childhood and into adulthood (e.g. Schier et al., 2003; Neil et al., 2006; Nardini et al., 2008; Gori et al., 2008; Innes-Brown et al., 2011; Nava & Pavani, 2013). It also seems that semantic associations across the senses influence perception throughout development. For example, Jordan & Baker (2011) found that redundant audiovisual information

helped 3- to 5-year-olds' numerical matching performance, compared with unisensory information; suggesting that at this age children can already benefit from crossmodal semantic associations. Here, we investigate how children (and adults) bring together concurrent complementary or conflicting sensory information presented in vision and audition. It seems that semantic associations play a role in perception from early in development, however it is less clear how this role develops. It is possible that across development the role of semantic knowledge in multisensory perception may become more established (e.g. Murray, Lewkowicz, Amedi & Wallace, 2016). Alternatively it could be that we observe an apparent increase in the role of semantic associations with age, however this is driven by strengthening associations rather than a more general change. To disentangle these two possibilities we present children (and adults) with audio-visual pairings which they are familiar with and also introduce new audio-visual pairings to explore their relative influence. To this end, we used a Stroop-like paradigm (Stroop, 1935) in which participants were required to attend to and identify a sound while simultaneously being presented with a visual stimulus.

Children are susceptible to various forms of Stroop interference. From around 7 years of age children experience a large degree of interference for the classic color-word Stroop paradigm (Comalli, Wapner and Werner, 1962). From around 3 years of age children are susceptible to Stroop interference in tasks, which do not require reading ability (e.g. Gerstadt, Hong & Diamond, 1994; Wright, Waterman, Prescott & Murdoch-Easton, 2003; Prevor & Diamond, 2005). Across all these latter studies children were slower to name an item when it was presented alongside semantically incongruent information.

In crossmodal Stroop paradigms, participants are typically asked to attend to a stimulus presented in one modality, while ignoring a stimulus presented in another modality. Participants tend to be slower to respond to a stimulus presented in one modality when it is accompanied by an incongruent stimulus presented in another modality (e.g. Cowan and Barron, 1987; Vogler and Titchener, 2011). Yuval-Greenberg and Deouell (2009) investigated the influence of visual stimuli on auditory processing, as well as the influence of auditory stimuli on visual processing. They presented adult participants with pictures and vocalizations of animals, which had either a congruent, incongruent or neutral relation to one another. They found an asymmetry in the extent to which one modality influenced the other. Participants were faster to respond to congruent trials irrespective of which modality they were responding to, however this advantage was greater when participants were responding to the auditory stimulus. It seems that in adults, visual stimuli confer a particular advantage for recognition of auditory stimuli. However, evidence from the developmental literature (e.g. Napolitano & Sloutsky, 2004; Robinson & Sloutsky, 2004; Massaro et al., 1986; Nava & Pavani, 2013) suggests that younger children may be less influenced by visual information, and in fact, demonstrate an auditory dominance bias.

Crossmodal Stroop has also been explored developmentally. For example, Hanauer and Brooks (2003) found that from 4 to 5 years of age children were slower to respond to a color patch when the auditory distractor was an incongruent color word rather than a non-color adjective. The extent of this interference (difference in reaction times between conditions) decreased with age and the effect was relatively small in adults. In a later study, Hanauer and Brooks (2005) found that between 3 and

7 years of age children were slower to respond to a line drawing when the auditory distractor was from the same rather than a different semantic category. Again the extent of this interference reduced with age and the extent of interference was mediated by whether the distractor item was from the same response set (e.g. animals versus clothes). These studies suggest that crossmodal semantic associations influence children, however the task irrelevant information was always a word. Thus, these studies do not inform us about whether non-verbal information is automatically processed at a semantic level.

Studies of sensory dominance suggest that early in development auditory stimuli tend to dominate perception (Napolitano & Sloutsky, 2004; Robinson & Sloutsky, 2004; Massaro et al., 1986), whereas this bias tends to be reversed in adulthood (e.g. Howard & Templeton, 1966; McGurk & MacDonald, 1976; Colavita, 1974). Developmental studies have demonstrated the potential time course of this change. Constantidou et al., (2011) found that children's (7 to 13 years of age) memory for spoken words presented with a visual stimulus was better than alone, however this performance was not better than for visual stimuli alone. This might be because memory for spoken words was enhanced by visual stimuli, or might be due to a visual dominance effect, which appears to emerge from 7 years of age (Nava & Pavani, 2013). Heikkila & Tiippana (2016) also demonstrated that 8- to 12-year-olds had better recall for stimuli presented in semantically congruent audiovisual pairs than for stimuli presented in non-semantic pairs. Incongruent pairs did not interfere with recall. Thus, it seems that semantically congruent information can enhance recall in childhood. As such, it seems that children can link semantic information across audition and vision, and use this to encode a single item.

The aim of the present study was to investigate the following questions: (1) Do primary-school-aged children benefit from semantically congruent audio-visual information during auditory object recognition and/or are they disadvantaged by incongruent audio-visual information? (2) With development does knowledge of semantic associations play an increasing role in combining sensory stimuli, or is this influence constant and instead the semantic associations become more robust?

In the current study we ask children to focus on information presented in the auditory domain, whilst ignoring information presented in the visual domain. We chose to investigate children between 5 and 9 years of age as previous research has shown some evidence of multisensory integration and perceptual benefits (e.g. Nardini, Bales & Mareschal, 2015) across this age range, but typically not at a mature level. We present participants with audio-visual pairings which they are familiar with, and audio-visual pairings which have been introduced during the experiment, this allows us to tease apart two potential trajectories for the development of semantic associations in multisensory perception; (i) the role of semantic associations changes across development, (ii) semantic associations become robust with development, which leads to a change in their role. Given the existing literature on sensory dominance, we predict that younger children will be less susceptible to Stroop-like interference from conflicting visual information than adults, in turn this may also lead to less facilitation from redundant visual information. Throughout the experiment participants are given the task of identifying an animal vocalization, whilst ignoring task irrelevant visual information. This animal vocalization is presented simultaneously with a visual stimulus, which is either congruent (same animal),

incongruent (different animal), or neutral (black and white pattern). An auditory prompt is then presented (the name of an animal). If this prompt matches the previous vocalization then participants are required to make a button press.

Methods

Participants

Fifty-nine children contributed data to this study (32 females and 27 males). Children ranged in age from 6.0 years to 9.42 years. Children were divided into two age groups; 6 to 7-year-olds (n=26; M = 7.12 years; SD = 0.54; Range = 6.0 to 7.89 years) and 8 to 9-year-olds (n=33; M 8.75; SD = 0.40, Range = 8.05 to 9.42). Ten additional children were excluded, 8 (M=7.00 years, SD=1.44, Range=5.33 to 8.91 years) children failed to reach 85% performance during practice trials, and 2 (one 5-year-old and one 8-year-old) children asked to stop the study before completing a sufficient number of test trials. Seventeen adults participated (ten females, seven males), ranging in age from 18 to 53 years (M = 27.70; SD = 7.88). An additional adult was excluded as she failed to reach 85% performance during the practice trials. All participants had normal or corrected to normal vision and hearing. The age range of adults participating in the study was quite large. All but two of our participants ranged in age between 19 and 29 years. To check whether these older participants should be considered separately from the younger adults in our study we removed them and re-ran our analyses, this produced the same pattern of results and as such the full group of adults is reported on.

Apparatus and Stimuli

The current study adapted a paradigm designed by Yuval-Greenberg and Deuoell (2009). The experiment was conducted using a Hewlett Packard G600 laptop computer, with a resolution of 1280 by 800 and a refresh rate of 60Hz. Stimulus programming, presentation, and response collection was carried out using E-Prime version 2 (http://www.pstnet.com/). Visual stimuli presented in the test trials of the experiment consisted of colored photographs of eight animals (lion, sheep, koala, meerkat, dog, rhino, raccoon, and elephant) presented on a white background, as well as black and white checkerboard/dot patterns, all presented for 500ms. Three images were used as exemplars for each animal, resulting in 24 different animal images (see Figure 1). Auditory stimuli presented in the test trials consisted of eight animal vocalizations (lion, sheep, koala, meerkat, dog, rhino, raccoon, and elephant). Vocalizations were selected from an online database of naturally recorded sounds (freesounds.org), they were all processed using a freely available programme (Audacity) to have a sampling rate of 44100Hz, a resolution of 16 bits per sample and were normalized to their maximum amplitude. Each vocalization was represented by three exemplars, leading to a total of 24 animal vocalizations. Sounds were edited to fill the 500ms interval using Audacity. In some cases this meant selecting a section of the full vocalization (e.g., raccoon chattering). In other instances this meant repeating a single vocalization (e.g., dog barking). Auditory prompts were also presented. These consisted of the names of the aforementioned animals, spoken in a natural female voice. Auditory prompts were recorded using a Yoga EM-278 microphone. Additional auditory and visual stimuli were presented during practice trials; these were sounds and images of bears, cows, frogs, cats and deer. All auditory stimuli were presented binaurally through a set of Sennheiser HD201 stereo headphones at 55dB. Participants responded using the space bar situated within the laptop keyboard.

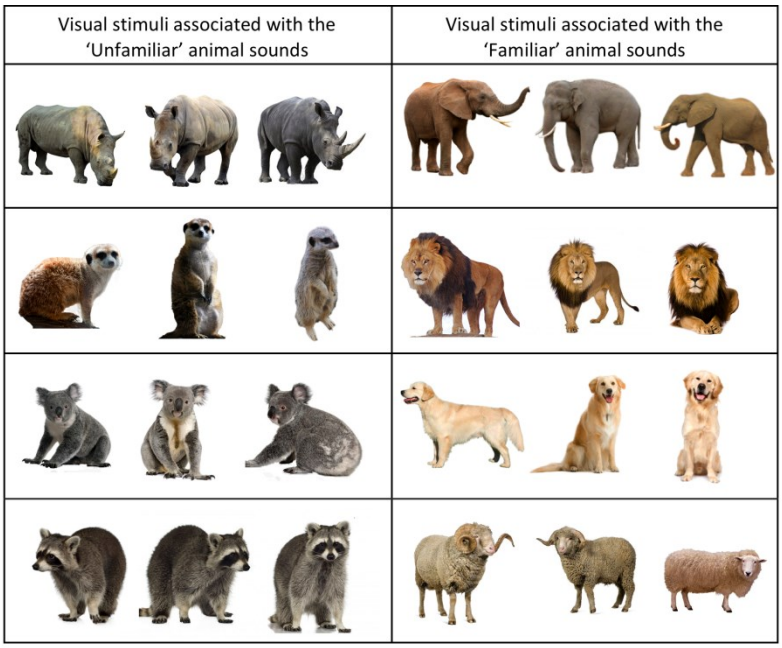

Figure 1: Visual stimuli presented in the experiment. 'Newly Learned' images were presented in the familiarization phase and in test trials. 'Familiar' images were only presented during test trials.

Procedure

Participants were tested individually, in a quiet room. They were seated at a desk with the computer positioned approximately 30cm in front of them. The study consisted of four parts (see Figure 2).

Familiarity check: Initially participants were presented with one exemplar of each of the eight animal vocalizations and were asked to name an animal that they thought might make this sound. This was a free response, so participants could name as many animals as they wanted. This gave a measure of whether the selected auditory stimuli were truly 'familiar' or unfamiliar to each participant at the start of the study.

	Familiarity check	Practice	Learning	Test trials
Images	None	Congruent, Incongruent and Neutral	Congruent and Neutral	Congruent, Incongruent and Neutral
Sounds	1 exemplar of each: Koala, Raccoon, Meerkat, Rhino, Lion, Dog, Elephant and Sheep	Bear, cow, frog car and deer	Newly Learned: Koala, Raccoon, Meerkat and Rhino	Newly Learned: Koala, Raccoon, Meerkat and Rhino Familiar: Lion, Dog, Elephant and Sheep
Trials	8	9	48	144
Feedback	No	Yes	Yes	No
Trial structure	Free response	Button press if prompt and sound match	Button press if prompt and sound match	Button press if prompt and sound match

Figure 2: Description of each phase of the experimental procedure.

Participants were then told that they were going to play a computer game in which they would hear an animal sound, and at the same time they would see a picture. This picture could be of the same animal, of a different animal, or might not be related to the sound at all. They were told that next they would see a question mark on the screen and that they would hear a lady's voice saying the name of an animal. If the lady named the animal that they had heard then they should press the indicated key, as quickly as possible. However, if the lady said the name of any other animal, then they should not make any response. We decided to use a single key for children (and adults) to record their responses as previous research (e.g., Davidson, Amso, Anderson & Diamond, 2006) has demonstrated that participants are slower to respond to trials that require a different response site to the previous trial (even though this response is made with a different finger). Furthermore, the extent of this delay is

mediated by task and age. Finally, because we excluded trials in which participants responded incorrectly, we independently examined response speed rather and accuracy.

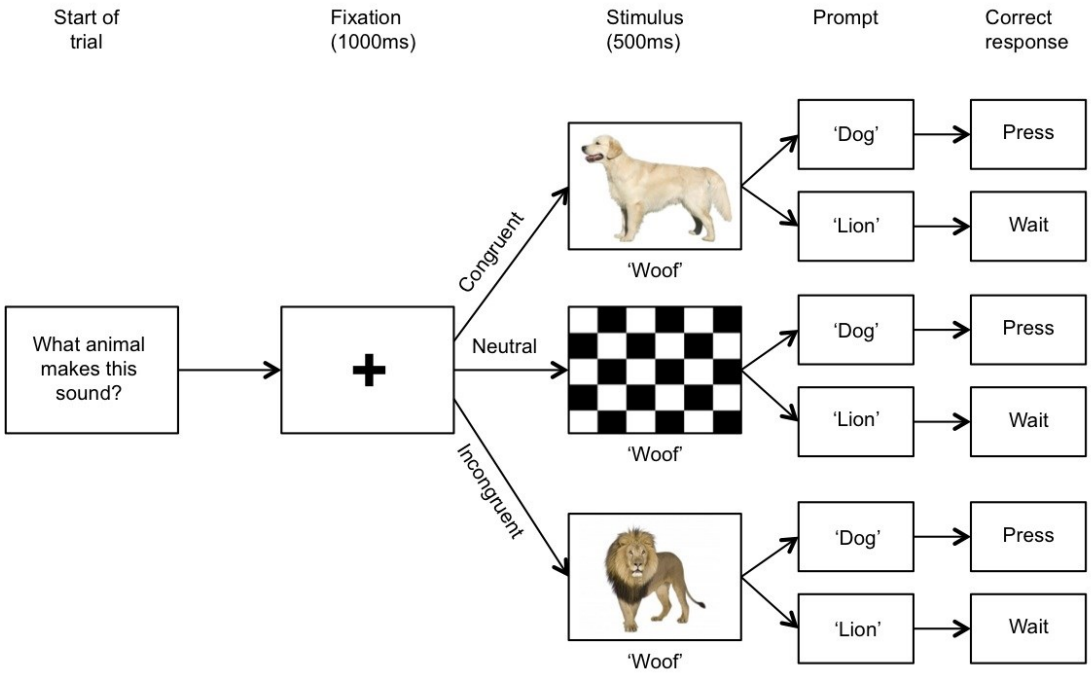

Figure 3: Schematic of the structure of a trial.

Practice trials: Participants were informed that they would have a chance to practice the game to make sure that they understood the rules. They then completed nine practice trials, which had the same structure as the test trials (see Figure 3 for a schematic of the sequence of events within a single trial); however, the stimuli presented in these practice trials were not subsequently repeated.

Each trial began with text on the screen that read 'What animal makes this sound?' This text was read aloud to children. The experimenter initiated a trial when the participant was ready. A black fixation cross then appeared on the screen and

remained there for 1000ms. Next, an image appeared on the screen. This image either showed an animal or a black and white pattern. At the same time, an animal vocalization was presented. The animal vocalization and image were either from the same animal (Congruent), from different animals (Incongruent), or, the animal sound was presented with a neutral image (Neutral). During practice trials participants were given feedback on both their performance (correct or incorrect) and their speed of response, this was presented as text on the screen and read aloud to children. If participants did not respond correctly to at least 85% of trials, then they were presented with a further nine practice trials. If participants did not respond correctly on at least 85% of trials after two practice sessions, then they were excluded from participating in the remainder of the study.

Learning phase: The next phase of the study gave participants experience with 'Newly Learned' animal vocalizations. During this phase participants were presented with the vocalizations of raccoons, koalas, meerkats and rhinos. During piloting, these sounds were identified as being unfamiliar to the majority of British children and adults (participants were unable to identify which animal produced these sounds given the opportunity to give as many suggestions as they could). The structure of the trials was the same as described above (and shown in Figure 3), however, participants were only presented with Congruent or Neutral trials. The purpose of this phase of the experiment was to give participants experience of the animal vocalizations and their associated images. In this phase, participants were given feedback on their performance, and when they gave an incorrect response they were informed of the correct answer. Participants completed 48 training trials (24 Congruent, 24 Neutral) with half of these trials requiring a button press as a correct response. Participants

were exposed to each type of Newly Learned animal sound (e.g., Koala) 12 times, with each specific sound being repeated 4 times. During Neutral trials these were presented with one of the black and white neutral stimuli described above, selected at random on each trial. During Congruent trials these were presented with one of the three possible Congruent animal images, selected at random on each trial. We included Neutral trials in this phase of the experiment to ensure that children were learning the auditory information presented. Prior to the experiment children had some knowledge of the image of these animals, but no knowledge of the sounds they made. Including Neutral trials meant that they had to use purely auditory information to respond and were given feedback if this response was incorrect.

Test trials: The final phase of the experiment required participants to play the same 'game' again. Trials again had the same format as described above (and shown in Figure 3), however participants were not given any feedback about their responses. They completed two blocks of 72 test trials, each block comprising 24 each of Neutral, Congruent, and Incongruent trials in a random order. Two thirds of these trials were accompanied by the correct prompt, and so a button press was the correct response. On the remaining trials, withholding a button press was the correct response. Participants were reminded to respond as quickly and accurately as possible.

Results

The categorization of 'Familiar' and 'Newly Learned' animal sounds held true for all participants tested. During the initial familiarity check, none of the participants were able to label a 'Newly Learned' animal sound correctly, whilst all participants were

able to name the 'Familiar' animal sounds. Therefore, no participants were excluded based on these data.

Accuracy:

Performance was high for all age groups (see Figure 4). An analysis of variance on the proportion of correct trials was performed with *Congruency* and *Familiarity* as within-subjects factors, and *Age group* as a between-subjects factor. This revealed a main effect of *Familiarity* [$F(1, 73)=45.297$, $p<0.001$, $\eta^2_p=0.383$], overall participants made more correct responses during Familiar (M=89.2%, SE=1.0) trials than Newly Learned trials (80.9%, SE=1.2). This analysis also revealed main effects of *Age group* [$F(1, 73)=7.342$, $p<0.001$, $\eta^2_p=0.167$], and *Congruency* [$F(2, 146)=4.647$, $p=0.011$, $\eta^2_p=0.060$]. A significant interaction emerged between *Familiarity* and *Congruency* [$F(2, 146)=4.473$, $p=0.013$, $\eta^2_p=0.058$]. Neither the interaction between *Congruency* and *Age Group* [$F(4,146)=1.226$, $p=0.302$, $\eta^2_p=0.033$], *Familiarity* and *Age Group* [$F(2,73)=1.138$, $p=0.326$, $\eta^2_p=0.30$] nor the three-way interaction [$F(4,146)=0.542$, $p=0.705$, $\eta^2_p=0.015$] reached significance.

The main effect of Congruency was explored using Bonferonni corrected paired samples t-tests. These revealed that participants made significantly more correct responses in the Congruent (M=87.7%, SE=1.0) than Incongruent (M=84.8%, SE=1.1) condition [$t(76)=3.822$, $p<0.001$, $d=0.33$]. No other significant differences emerged between conditions.

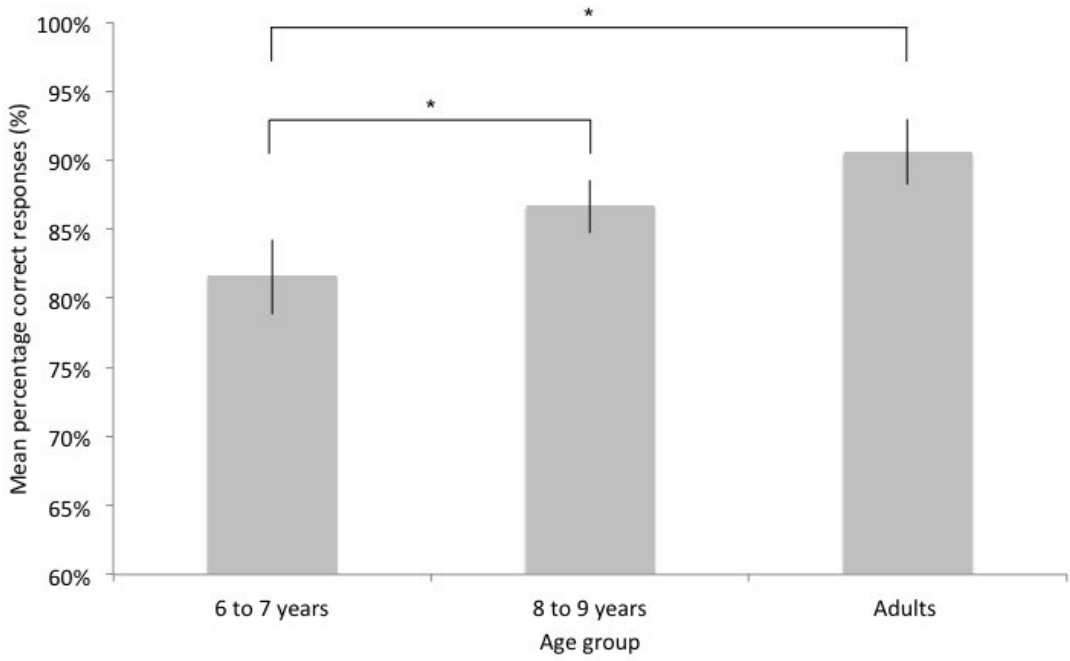

Figure 4: Mean percentage of correct responses, averaged across conditions for each Age group. Error bars plot standard error.

Bonferroni corrected pairwise comparisons also revealed that Adults (M=90.5% correct, SE=1.9) made significantly fewer errors than the 6 to 7-year-olds (M=81.4% correct, SE=1.5, p=0.001, d=1.16), see Figure 4. The 8 to 9-year-olds (M=86.6% correct, SE=1.4) also made significantly fewer errors than the 6 to 7-year-olds (p=0.042, d=0.64).

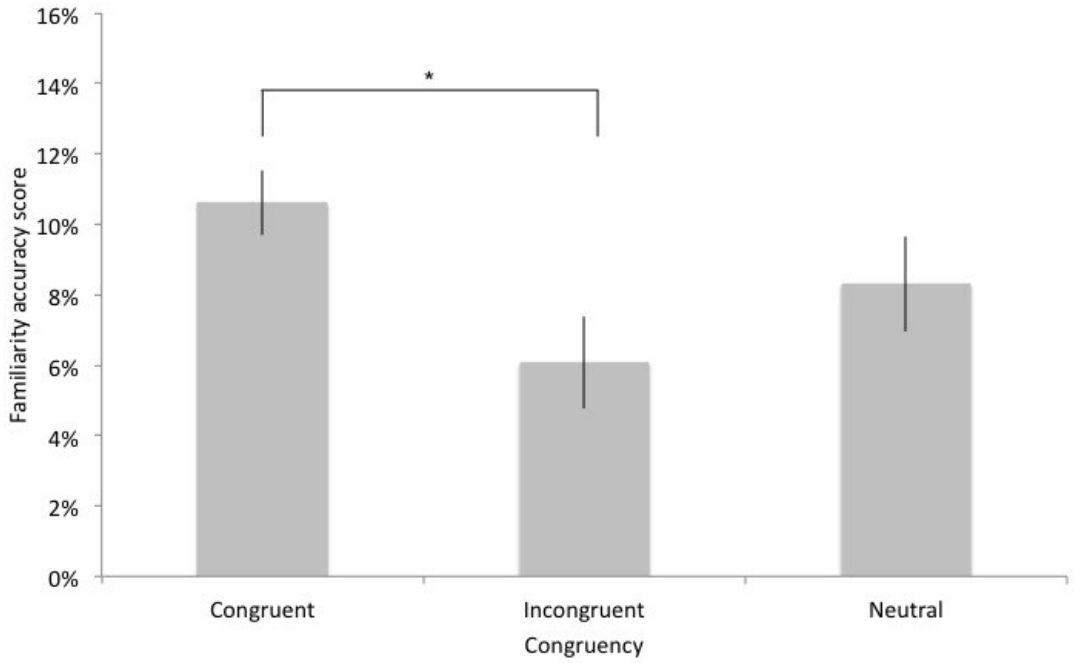

Figure 5: Familiarity accuracy score calculated by subtracting percentage correct in Newly Learned trials from percentage correct in Familiar trials. A positive score indicates that accuracy was higher for Familiar compared to Newly Learned trials. Error bars plot standard error.

To further explore the interaction between *Familiarity* and *Congruency* paired samples t-tests were conducted comparing performance across the Familiar and Newly Learned conditions for each *Congruency* condition. These revealed that participants made significantly fewer errors in the Familiar than Newly Learned trials for every Congruency condition ($p<0.001$ in all instances). To further unpack this interaction a Familiarity accuracy score was calculated by subtracting the mean percentage of correct responses made in the Newly Learned condition from the mean percentage of correct responses in the Familiar condition, for each Congruency condition (see Figure 5). Paired samples t-tests were then performed on these scores across Congruency conditions. These revealed that the Familiarity accuracy score was significantly larger in the Congruent condition (M=10.6%, SE=1.12) than the Incongruent condition (M=6.0%, SE=1.30), [$t(75)=2.987$, $p=0.004$, $d=0.42$]. Thus,

performance was best when the auditory stimulus was Familiar and presented alongside a Congruent visual stimulus. At the other extreme, performance was worst when the auditory stimulus was Newly Learned and presented alongside an Incongruent visual stimulus. There were no other significant differences across congruency conditions.

In summary, analysis of accuracy across conditions revealed that the youngest children performed the worst and that performance increased with age. Participants made more errors when the auditory stimulus was paired with an Incongruent visual stimulus than when it was paired with a Congruent visual stimulus. This effect did not interact with age, suggesting that all age groups were similarly influenced by the relationship between the auditory and visual stimuli. Participants also made more errors in the Newly Learned condition, in which the auditory stimuli were unknown to them before they were introduced during the experiment. Again, this did not interact with age group, suggesting that participants were similarly affected by the depth of knowledge they had of the pairings, irrespective of age. Participants were most accurate when they were asked to recognize an auditory stimulus that was familiar to them, and this was presented with a congruent visual stimulus. As might be expected, accuracy was worst when participants were asked to recognize an auditory stimulus that they had limited experience with, which was presented with an incongruent visual stimulus.

Reaction times:

A third of experimental trials were excluded as the prompt was invalid (when the prompt and vocalization did not match participants were not required to respond), this

was independent of whether the trial was Congruent, Incongruent or Neutral. Analyses were then performed only on trials, which participants responded to correctly. Mean reaction times and standard deviations were calculated for each participant. Trials in which reaction time fell further than +/- 3 standard deviations from a participant's mean reaction time in each condition were excluded as outliers. Finally, reaction times below 150ms were also excluded, as any response below this time was assumed to be too fast for processing of the stimuli so was likely to be pre-emptive. This resulted in 2.9% of responses being excluded for the 6 to 7-year-olds, 3.4% for the 8 to 9-year-olds and 1.8% for the adults. Estimates of button press reaction times in adults range from around 200 to 250ms (e.g. Eckner, Kutcher and Richardson, 2010) so 150 ms is a conservative lower cut-off that should not exclude any genuine rapid responses. The remaining reaction time data were normally distributed in all age groups (as determined by the Kolmogorov-Smirnov test for normality).

Reaction times were analyzed in a mixed-design Analysis of Variance with *Familiarity* (Familiar or Newly Learned) and *Congruency* (Congruent, Incongruent or Neutral) as within-subjects factors, and *Age group* (6 to 7-year-olds, 8 to 9-year-olds and adults) as a between-subjects factor. The dependent variable was the mean reaction time to make a button press during valid trials. The ANOVA revealed main effects of *Familiarity* [$F(1,73)=267.198$, $p<0.001$, $\eta^2_p=0.785$], overall participants responded faster during Familiar (M=795ms, SE=19ms) trials than Newly Learned trials (M=1024ms, SE=19ms). This analysis also revealed main effects of *Congruency* [$F(2,146)=123.441$, $p<0.001$, $\eta^2_p=0.628$] and *Age group* [$F(4,73)=6.563$, $p=0.002$, $\eta^2_p=0.152$]. These main effects were qualified by significant interactions of

Familiarity with *Congruency* [F(2,146)=4.27, p=0.017, η^2_p=0.055] and *Familiarity* with *Age group* [F(2,73)=4.967, p=0.009, η^2_p=0.120]. The interaction of *Congruency* with *Age group* approached but did not reach significance [F(4,146)=2.206, p=0.08, η^2_p=0.196]. The three-way interaction between *Familiarity*, *Congruency* and *Age Group* did not reach significance [F(4,146)=1.395, p=0.240, η^2_p=0.037].

Paired samples t-tests were used to investigate the main effect of *Congruency*. Participants were significantly faster during Congruent trials (M=803ms, SE=18ms), than Neutral trials (M=953ms, SE=21ms), [t(75)=13.15, p<0.001, d=1.51]. Participants were also significantly faster during Neutral trials than Incongruent trials (M=1021ms, SE=21ms), [t(75)=4.34, p=0.001, d=0.49]. Finally, participants were significantly faster during Congruent than Incongruent trials, [t(75)=15.90, p<0.001, d=1.82]. Thus, participants responded most rapidly when an auditory stimulus was accompanied by a congruent visual stimulus, followed by a neutral visual stimulus, and were slowest to respond when the visual stimulus was incongruent.

The main effect of *Age group* was examined using Bonferroni corrected pairwise comparisons. These revealed that adults were significantly faster than both the 6 to 7-year-olds (p=0.006, d=1.15) and the 8 to 9-year-olds (p=0.004, d=1.09). There was no significant difference in average speed of response between the two child age groups.

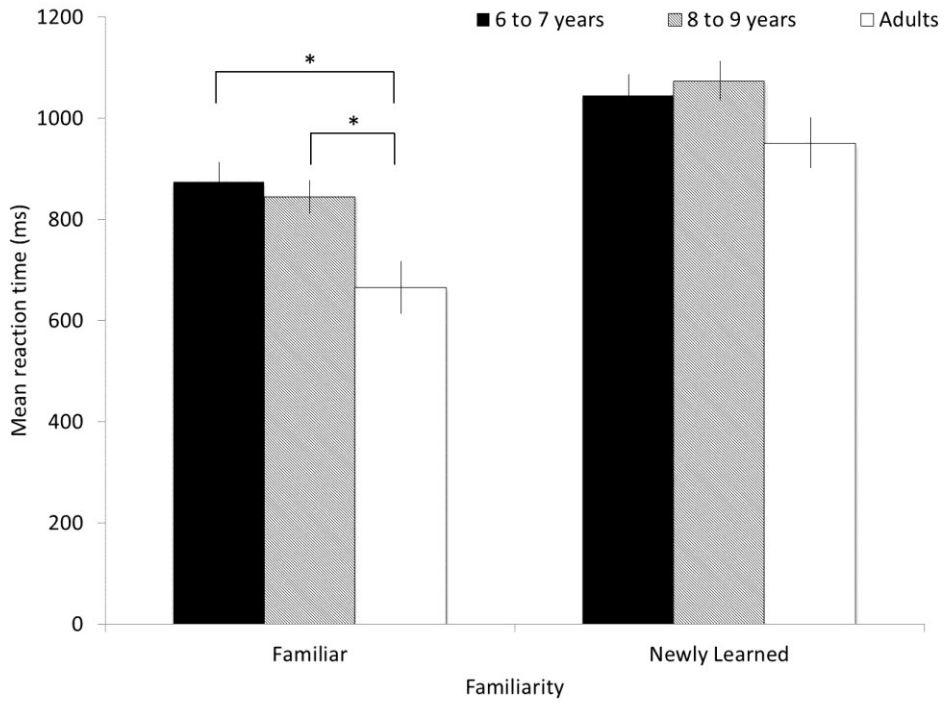

Figure 6: Mean reaction time to respond to the auditory prompt collapsed across Congruency condition, for Familiar and Newly Learned animal vocalizations within each Age group. Error bars plot standard error.

To explore the interaction between *Age group* and *Familiarity*, Bonferroni corrected, one-way ANOVAs were performed with *Age Group* as the between-subjects factor, independently for Familiar and Newly Learned trials (See Figure 6). These revealed that adults were significantly faster than the 6 to 7-year-olds ($p=<0.001$, $d=1.21$) and the 8 to 9-year-olds ($p=0.001$, $d=1.04$) in the Familiar condition, however no significant differences between age groups emerged in the Newly Learned condition. Thus it seems that when the auditory stimulus was Familiar adults had a significant advantage over children. However, when the auditory stimulus was Newly Learned performance for adults and children was similar.

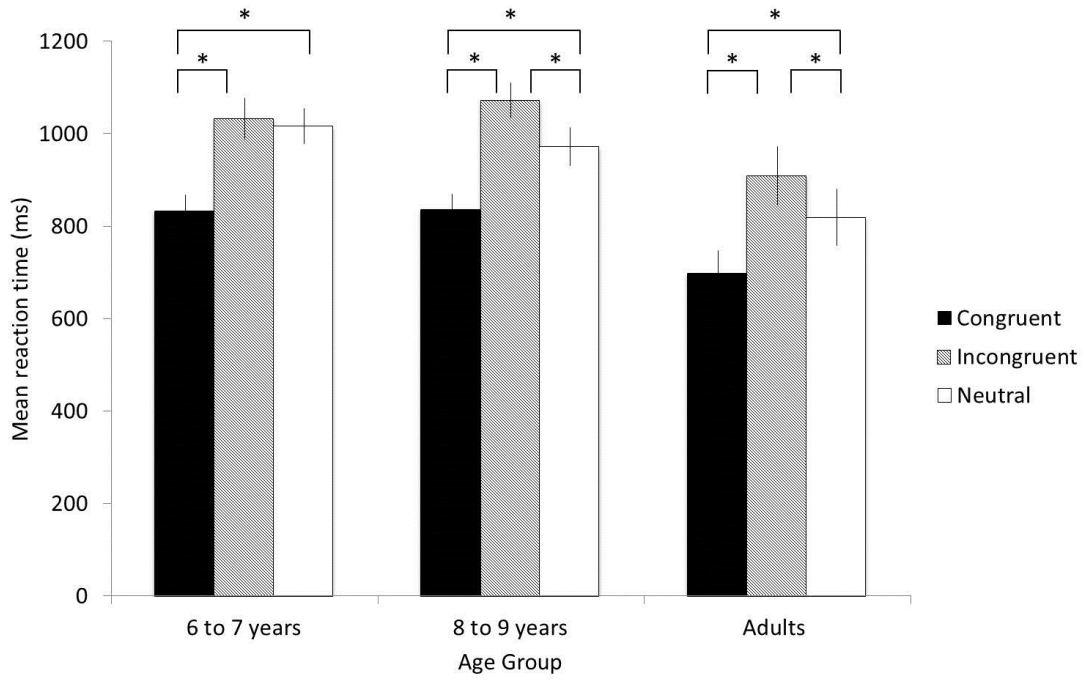

Figure 7: Mean reaction to the auditory prompt collapsed across Familiarity conditions. Error bars plot standard error.

To explore the marginally significant interaction between *Age Group* and *Congruency* (see Figure 7), paired samples t-tests were performed between *Congruency* conditions, independently for each *Age group*. These revealed significant differences in reaction times across all Congruency conditions (in the same directions as reported for the main effect of Congruency) for the 8 to 9-year-olds and adults ($p<0.001$ in all cases). For the 6 to 7-year-olds significant differences emerged between the Congruent and Incongruent trials ($p<0.001$, $d=1.20$), as well as between the Congruent and Neutral trials ($p<0.001$, $d=1.23$). However, the difference in reaction times to Incongruent and Neutral trials was not significant, [$t(25)=0.405$, $p=0.689$, $d=0.079$]. Thus, it seems that the older age groups are advantaged by a congruent visual stimulus and disadvantaged by an incongruent visual stimulus. In contrast at 6 to 7 years children are advantaged by a congruent visual stimulus, but are not significantly disadvantaged by an incongruent visual stimulus (as compared with

neutral). This may suggest that they are able to suppress irrelevant visual information; however, it could also be the case that the 'neutral' image is equally as interfering for younger children as the semantically incongruent image.

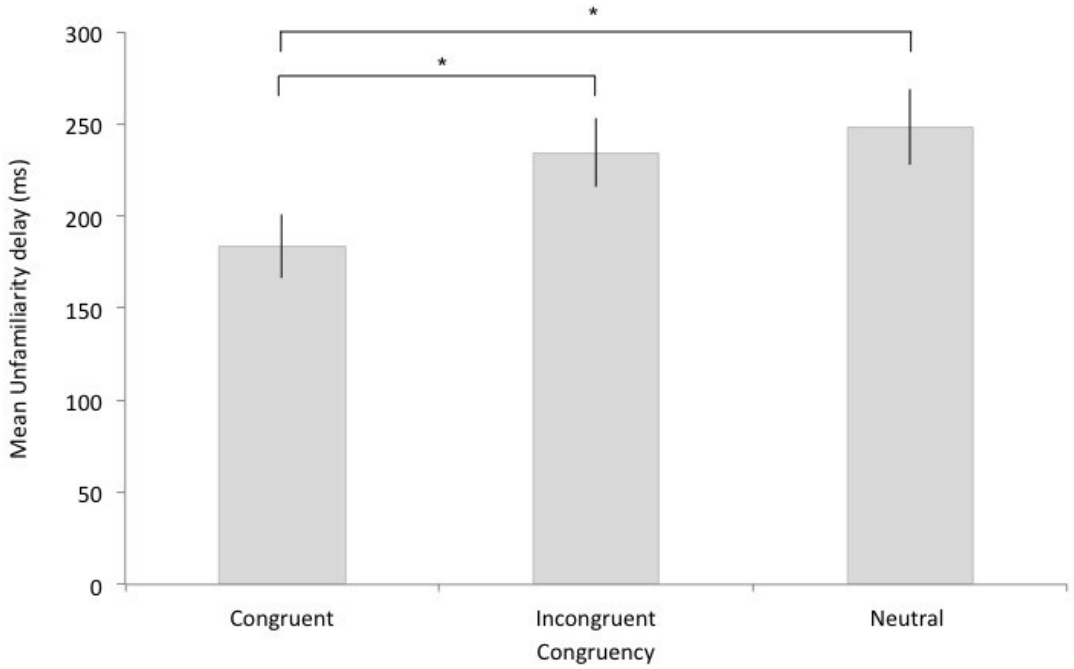

Figure 8: Mean Newly Learned disadvantage score (Newly Learned-Familiar reaction time). A positive value indicates that participants were faster to respond to Familiar than Newly Learned trials. Error bars plot standard error.

Finally, to explore the interaction between *Familiarity* and *Congruency* a Newly Learned delay was calculated (Newly Learned reaction time – Familiar reaction time) for each *Congruency* condition (see Figure 8). Paired samples t-tests were performed between *Congruency* conditions on these scores. Newly Learned delay was significantly smaller in the Congruent condition than the Incongruent condition [t(75)=2.534, p=0.013, d=0.32]. Likewise, Newly Learned delay was significantly smaller in the Congruent condition than in the Neutral condition [t(75)=2.752, p=0.007, d=0.39]. The difference in Newly Learned delay between the Incongruent compared to Neutral condition did not reach significance [t(75)=0.657, p=0.513,

d=0.08]. Thus, it seems that participants benefited more from the auditory stimuli being familiar when the relationship between the auditory and visual stimuli was either incongruent or neutral. When the relationship between the auditory and visual stimuli was congruent, familiarity had less impact on speed of responses.

In summary, at all ages tested, participants responded most rapidly during trials in which an auditory stimulus was accompanied by a congruent visual stimulus. This was followed by trials where the accompanying visual stimulus had no relation to the auditory stimulus. The youngest participants responded at a similar speed when the auditory stimulus was accompanied by either a neutral or incongruent visual stimulus. By 8 to 9 years of age, and in adulthood, participants were significantly slower to respond to trials where the auditory stimulus was accompanied by an incongruent visual stimulus.

The same order of reaction times (congruent, neutral, incongruent) emerged in both the Familiar and Newly Learned conditions, suggesting that participants had rapidly learned the new image and vocalization pairings, and that this association influenced their subsequent perception. It seems that even relatively limited experience with these pairings was enough to enhance perception when congruent stimuli were presented and to interfere with perception when incongruent stimuli were presented, however the extent of this influence was mediated by familiarity with the pairings.

When both children and adults knew the semantic association between the auditory and visual stimuli prior to the experiment, they responded significantly more rapidly than when they had learned these associations during the study. Adults (with the

opportunity to acquire extensive experience of the auditory stimuli across their lifetime) outperformed children at all ages when the auditory stimuli were familiar. However, when all groups had equivalent experience (when the auditory stimuli were unfamiliar at the start of the experiment) this advantage was no longer evident.

Discussion

In the current study we investigated how children and adults bring together current complementary or conflicting sensory information presented in vision and audition. Multisensory perception in adults seems to go beyond low-level stimulus properties and is also influenced by factors such as the congruency (in terms of both perceptual and semantic features) between the different sensory inputs (e.g. Heron, Whitaker & McGraw, 2004; Slutsky & Recanzone, 2001; Jackson, 1953). Here, we used a Stroop-like paradigm (Stroop, 1935) in which participants were required to attend to and identify a sound while simultaneously being presented with a visual stimulus. We presented participants with audio-visual pairings which they were familiar with, and audio-visual pairings which had been introduced during the experiment, allowing us to tease apart two potential trajectories for the development of semantic associations in multisensory perception; (i) the role of semantic associations changes across development, (ii) semantic associations become robust with development, which leads to a change in their role. Across middle childhood children appear to undergo a significant shift in their processing of audio-visual information; changing from an auditory bias to an adult-like visual bias (e.g. Nava & Pavani, 2013). This is also the period of time during which children begin to integrate information across the senses in a mature adult-like manner (e.g., Nardini, Jones, Bedford & Braddick, 2008; Gori,

Del Viva, Sandini & Burr, 2008; Nardini, Bedford & Mareschal, 2010; Nardini, Begus, & Mareschal, 2013; Petrini, Remark, Smith & Nardini, 2014; Jaime, Longard & Moore, 2014; Nardini, Bales & Mareschal, 2015). As such this is a particularly important period of development for us to explore the role of semantic associations across the senses.

We set out to address two key questions:

(1) Do school-aged children benefit from semantically congruent audio-visual information during auditory object recognition and/or are they disadvantaged by incongruent audio-visual information?

We found that stimuli presented in the task irrelevant modality (vision) influenced processing of stimuli in the task relevant modality (audition), from 6 years of age. This influence was demonstrated by differential reaction times across congruency conditions. Interestingly the pattern of reaction times across congruency conditions changed with age. From 8 years of age participants showed a significant facilitation effect when presented with a congruent stimulus in the task irrelevant modality, and a significant interference effect when presented with an incongruent stimulus in the task irrelevant modality. At 6 years of age, participants showed a significant facilitation effect, with significantly faster responses in the congruent condition compared to both the neutral and incongruent conditions. However, at this age participants did not demonstrate a classic interference effect; reaction times were very similar in the neutral and incongruent conditions. It appears that in this task facilitation effects emerge earlier in development than interference effects (relative to neutral), which

might suggest that the way semantic information is utilized changes with development. However, there are a number of possible explanations for the pattern of results, which emerged in the youngest age group. One possibility is that the youngest children found the 'neutral' visual stimuli and the incongruent visual stimuli equally distracting. This would suggest that at this age the influence of a visual distractor is not limited by its semantic association with the auditory stimulus. The fact that children were faster for congruent trials suggests they were taking the visual information into account. An alternative explanation of this finding could be that at this age children may process the visual stimuli faster than the auditory stimuli, and that it is this difference which allows them to be speeded in the congruent condition. If this were the case then performance in the other conditions might reflect children's speed of processing auditory information. Whilst the auditory dominance literature might predict (although primarily in younger ages) that auditory input is processed more rapidly due to its dynamic and transient nature, there are also studies suggesting that vision is processed preferentially (e.g. Colavita, 1974), or that speed of processing of stimuli is moderated by the stimuli being attended to (for a review see Spence & Parise, 2010). .In light of these varied hypotheses and our finding that 'neutral' visual stimuli were not processed differently to incongruent stimuli by the 6-year-olds, future research should include a unisensory baseline. Such a condition would give us further insight into the interaction between the senses and would allow for easier comparisons between this research and the literature investigating sensory dominance. Interestingly the increase in reaction times from congruent to neutral is similar in absolute terms across the age groups. If the youngest children were processing the visual information followed by the auditory information in serial order then you might expect that the interference effects they experienced would be

enhanced, which is not the case. In addition this age group do not seem to be preferentially processing auditory information over visual information (as might be predicted by the auditory overshadowing literature, e.g., Napolitano & Sloutsky, 2004; Robinson & Sloutsky, 2004; Massaro et al., 1986; Nava & Pavani, 2013) as this should lead to similar reaction times irrespective of congruency condition.

(2) With development does knowledge of semantic associations play an increasing role in combining sensory stimuli, or is this influence constant and instead the semantic associations become more robust?

The same order of reaction times across congruency conditions (congruent, neutral, incongruent) was observed for semantic associations introduced during the course of the experiment as well as for previously established associations. It appears that these associations were readily acquired throughout the course of the experiment and had an immediate impact on processing of the task relevant stimulus.

The extent of experience of semantic associations had a main effect on average response time, with faster responses being demonstrated for previously acquired (familiar) associations. In addition, the effect of extent of experience interacted with age. Adults (with extensive experience of previously acquired associations) were able to significantly outperform children in terms of response times when the auditory stimulus was familiar to them. However, when adults and children had equivalent experience of the auditory stimulus this speed advantage was negated. Given that developmental changes were only observed for familiar audio-visual pairings it appears that these changes are caused by experience-driven increases in the strength

of associations, rather than by maturational change in the role of semantic associations in multisensory processing. This finding is important to consider when comparing multisensory performance across development with performance in adulthood as it suggests that children could underperform not just because their perceptual system may be immature, but also because they have less experience with the stimulus pairings. This finding also suggests that, despite children and adults being able to rapidly form associations presented across their senses, such associations continue to mature over a protracted period. The fact that age interacted with familiarity suggests that the age effects we found cannot be explained away solely by more broad developmental changes such as general improvements in inhibitory skills. As such it seems that the influence of semantic associations on multisensory processing remains constant across the tested age range, but the associations themselves become more robust.

As the 3-way interaction did not approach significance we did not follow this up in the results section, however here we feel it is relevant to consider whether adults' speed in the Familiar trials could be attributed to certain *Congruency* conditions. Within Familiar trials adults were faster than children across all *Congruency* conditions, this might suggest that adults are speeded due to their experience with the auditory information, as congruency of visual stimulus didn't influence the effect.

In conclusion, as has been suggested in previous studies, visual information can have a potent effect on processing in other domains (e.g. Yuval-Greenberg & Deouell, 2009), even if this information is in a task irrelevant modality, and is semantically incongruent. Additionally, visual information can have a facilitatory effect on

processing of auditory stimuli even if the semantic association between these signals is newly acquired. We found this pattern of results from eight years of age. It appears that the influence of visual information on auditory object recognition might change between six and eight years of age.

Task irrelevant visual information influenced the processing of auditory stimuli from eight years of age. This influence occurred for both newly learned and well established audio-visual pairings. At this age children experienced significant facilitatory and inhibitory influences from vision on audition, suggesting they were not able to modify the use of visual information depending on its semantic relation to the auditory stimulus. Similar patterns of reaction times were evident for 8-year-olds and adults, suggesting that despite ongoing changes in multisensory processing across this age range (e.g. Nardini, et al. 2008; Gori, et al. 2008) there is some continuity in audio-visual interactions between 8 years of age and adulthood. The mechanisms behind these effects may vary across this age range but the result in terms of relative speed of processing is comparable.

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